Experimental Characterization of a Compact Gyroid-Pipe Heat Exchanger for Fuel Cell Powered Electric Aircraft Propulsion

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All-electric aircraft powered by a low-temperature polymer electrolyte membrane fuel cell (LTPEMFC) propulsion system has potential to achieve the strategic aims of low-emission flights by the year 2050. The challenge lies in regional flights with 70 passengers, which are not yet feasible with current technologies due to the low mass-specific power densities of the components in LTPEMFC system. This is particularly true for large components such as compressors and heat exchangers (HEXs), which are an essential part of the thermal management system and must become lighter, more compact and more efficient. HEXs designed using triple periodic minimal surface (TPMS) structures, such as gyroids, offer high compactness by increasing the heat transfer surface area per unit volume. This paper presents the design and experimental characterization of a compact gyroid-pipe heat exchanger (HEX) with embedded coolant channels. The aim of this study is to determine the thermal-hydraulic performance of the gyroid-pipe HEX and to compare it with that of a baseline louver-plate-fin HEX. The requirements for the HEX rating and sizing is derived from a conceptual regional aircraft propulsion topology. The design and prototype of small-scale HEX, together with a modular test setup are developed. Several trade-off cases are tested using take-off boundary conditions and performance results are used to determine the characteristics of the gyroid-pipe HEX and its thermal management system. Based on small-scale HEX results, size estimations are made for the requirements of a full-scale propulsion unit. Fig. 1 shows the workflow.

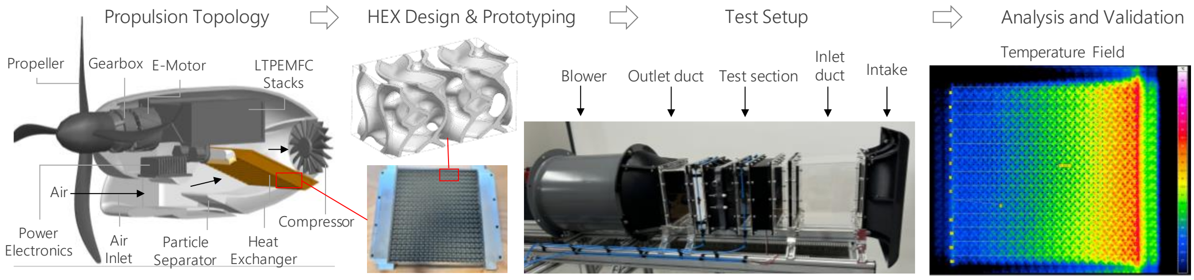

Fig. 1: Workflow: all-electric propulsion topology, design of gyroid-pipe HEX, test rig and result.

The characteristics of a HEX can be measured in terms of its combined thermal and hydraulic performance, including compactness and fin efficiency. Very few analytical correlations are available for estimating the performance of HEXs based on TPMS geometries, which enhance the heat transfer surface area in a relatively small volume. This study tests and compares a 3D-printed gyroid-pipe HEX (cross-section 20 cm x 20 cm, depth 2 cm) with an off-the-shelf louver-fin-plate HEX. The output heat duty, or heat transfer rate, is measured as the product of the mass flow rate, the specific heat capacity, and the temperature difference across the HEX at the air and coolant sides. The pressure drop inside the HEX is measured using differential pressure sensors on the air and coolant sides. Pumping power is calculated as the additional power required by the blower and coolant pumps to overcome pressure losses within the HEX. The power ratio is defined as the ratio of the heat transfer rate to the total pumping power. Roadmaps for PEM-based propulsion technology estimate a power ratio of 5 or more, alongside a desired power density of 10 kW/kg. Tests are conducted at coolant inlet temperatures ranging from 60 to 80 °C, coolant flow rates ranging from 1 to 5 l/min, and air speeds of up to 30 m/s. The heat transfer rate and total pumping power increase with higher air speeds and coolant flow rates. The power ratio drops exponentially with higher air flow rates as pumping power increases. For constant air and coolant flow rates, gyroid-pipe HEX delivers a lower heat duty than louver-fin-plate HEX due to higher pressure losses on the air side. Test results show that a maximum heat rejection of 5.5 kW is possible with gyroid-pipe HEX at a coolant flow rate of 5 l/min and an air mass flow rate of 0.6 kg/s, giving a power ratio of 5. A similar heat duty can be achieved with louver-fin-plate HEX at a coolant flow rate of 3 l/min, with a much higher power ratio of 21, and with 75% lower pumping power, indicating better thermal-hydraulic performance but with larger mass and volume than gyroid-pipe HEX. Gyroid-pipe HEX results in a mass-specific power density of 5 kW/kg and a volumetric power density of 6.9 MW/m³, which is 3.25 and 2.3 times higher than that of louver-fin-plate HEX, respectively. At the above operating point, the gyroid-pipe HEX would require two large segments, each measuring 1 m x 2 m, for a total heat rejection capacity of 500 kW in each of the total ten propulsion system units. The full paper provides a detailed experimental assessment of the different trade-offs, HEX sizing and integration.